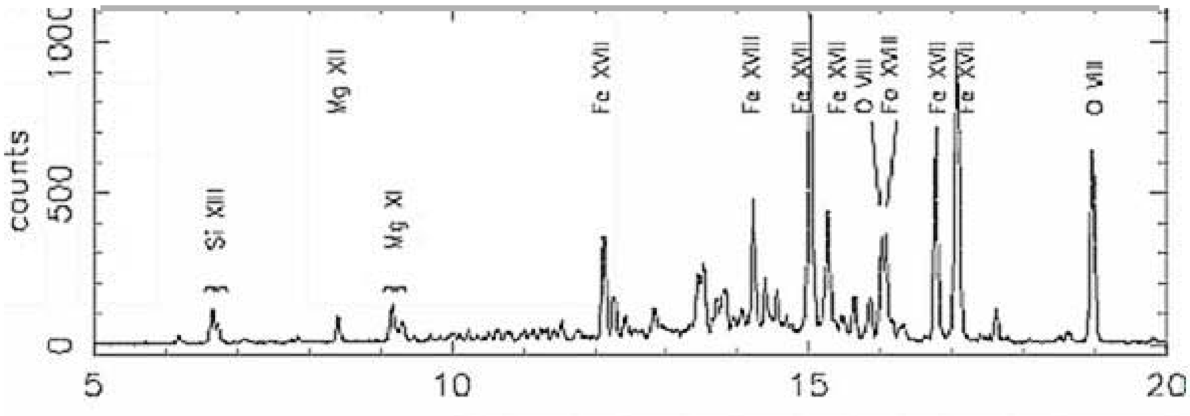
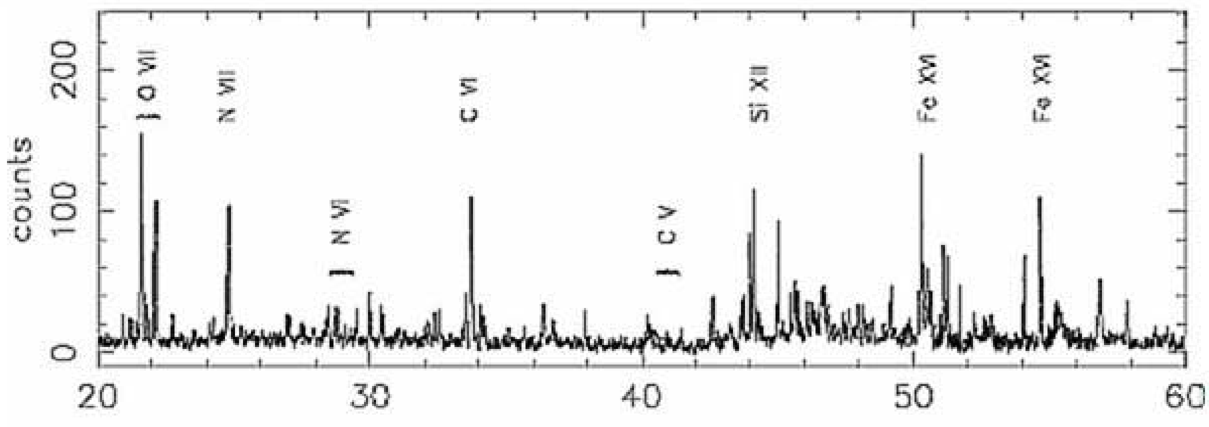
The Off-Plane Option for the Reflection Grating Spectrometer

Webster Cash

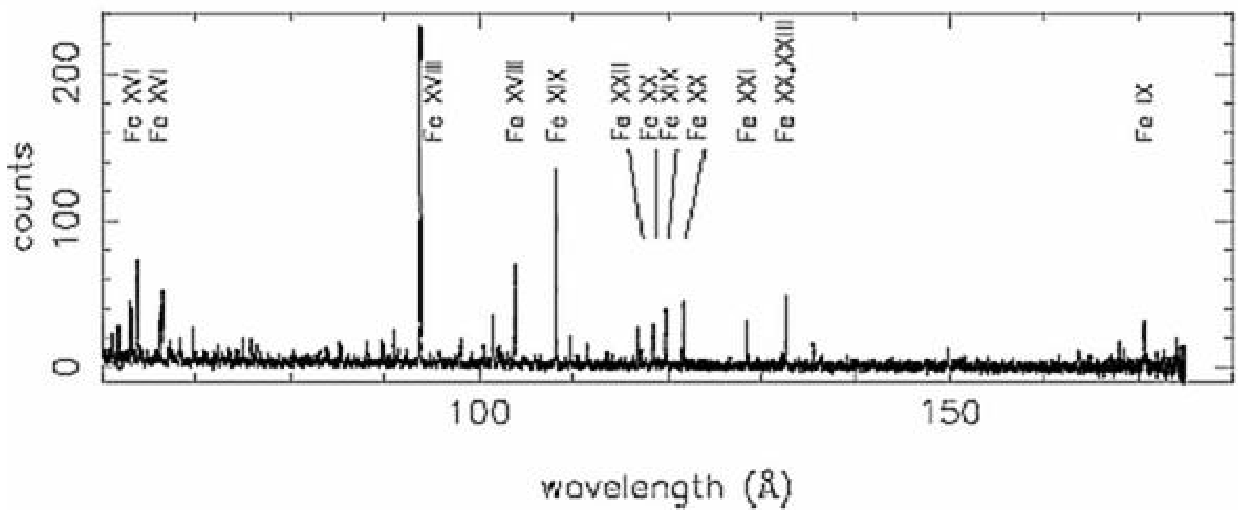
University of Colorado



Chandra Spectra Look Like Traditional Ground Spectra.

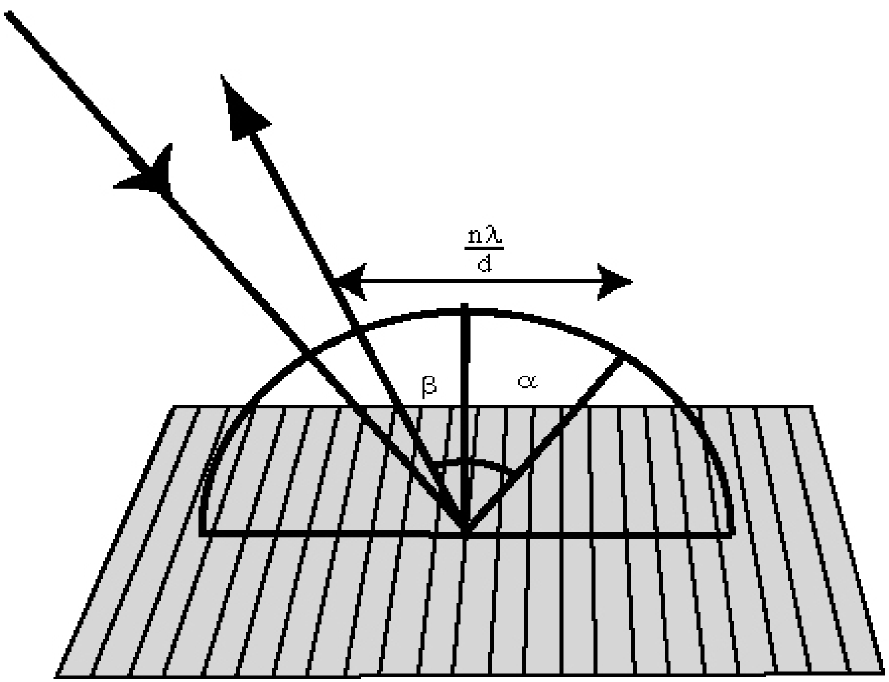


Can We Afford to Step Back???



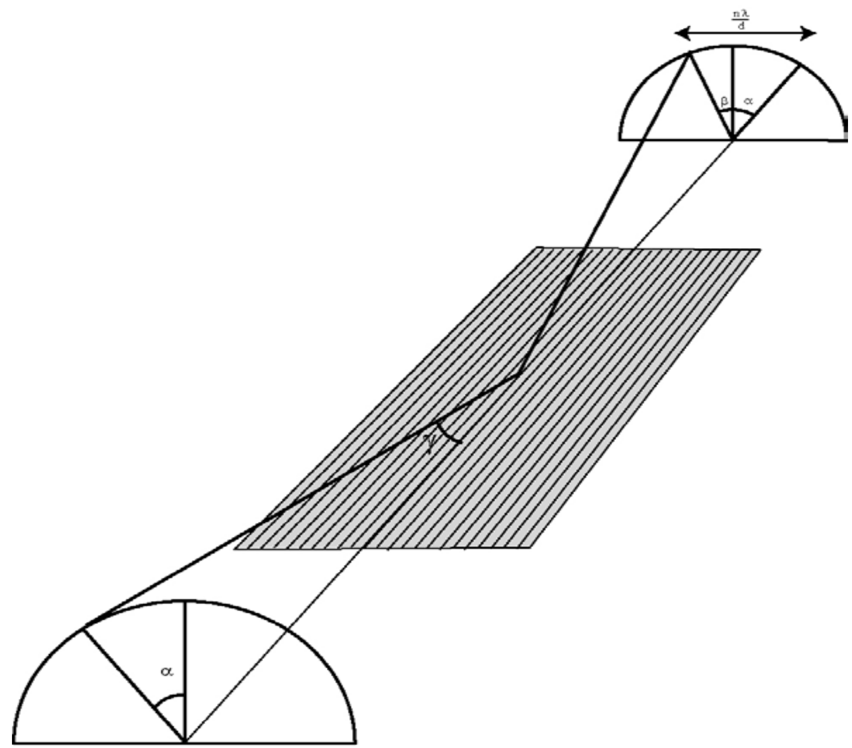
In-plane Mount

$$\sin\alpha + \sin\beta = \frac{n\lambda}{d}$$

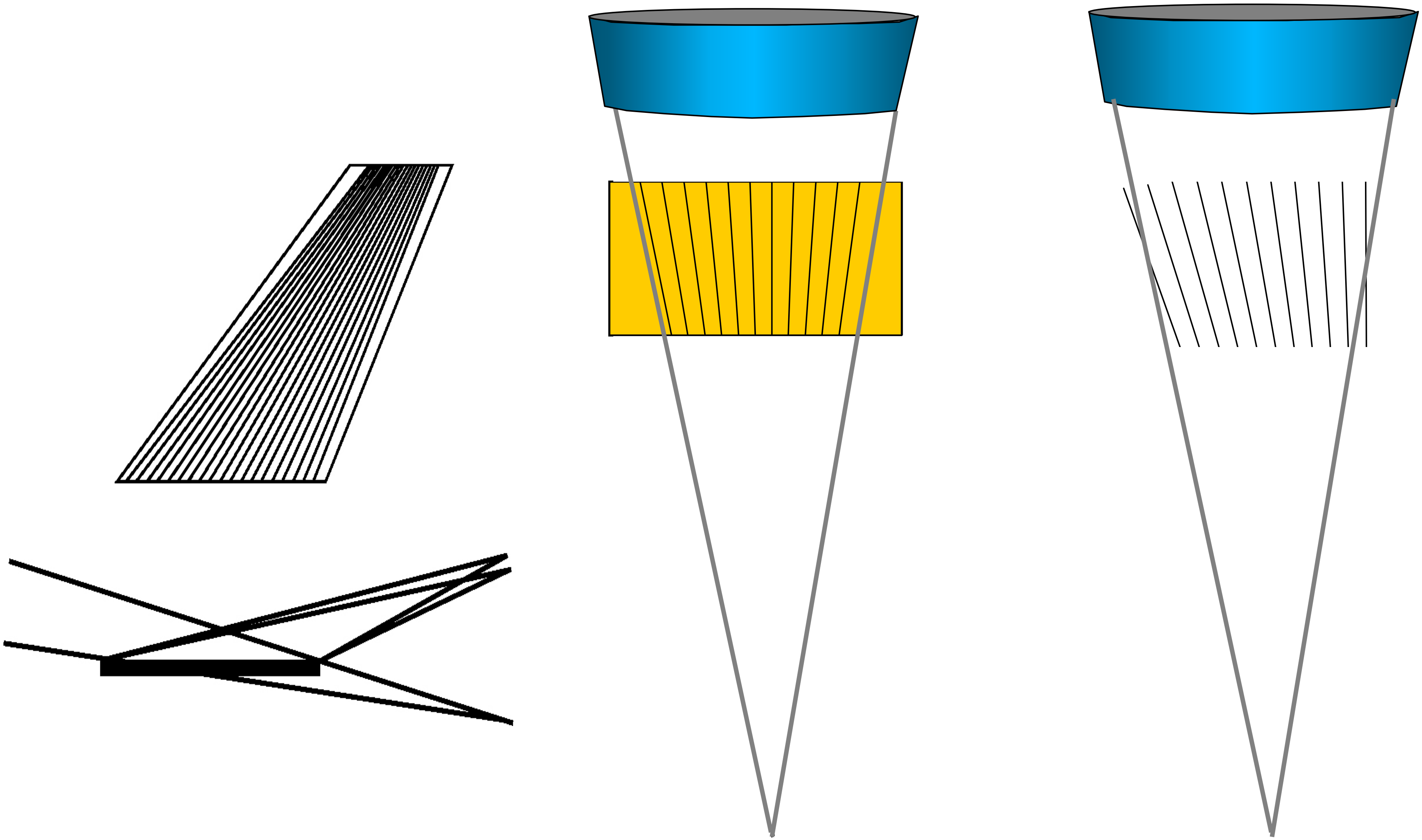


Off-plane Mount

$$\sin\alpha + \sin\beta = \frac{n\lambda}{d\sin\gamma}$$



Radial Groove Gratings



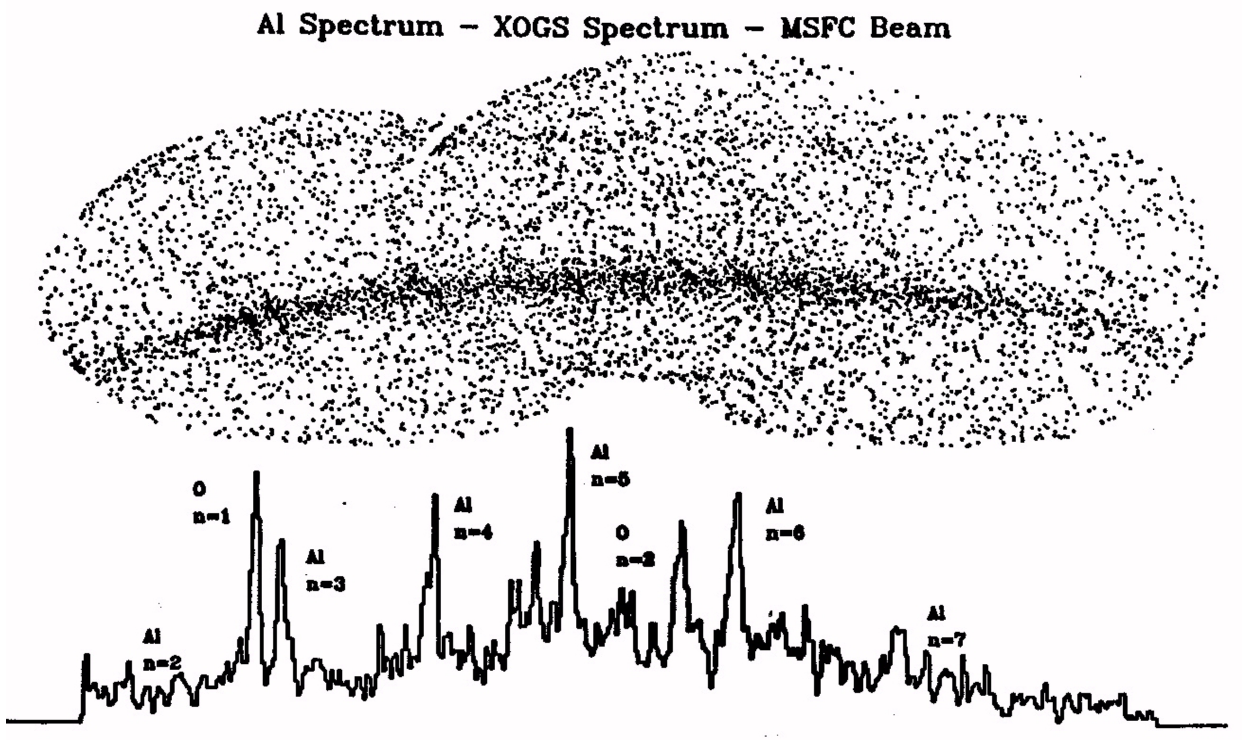
Off-plane Resolution

$$R = \frac{(\sin\alpha + \sin\beta)\sin\gamma}{B\cos\alpha}$$

At typical values of off-plane angles and 15” telescope resolution
R ~ several hundred → thousand

Sub-Aperturing improves it further

An Off-plane X-ray Spectrum



Spectrum from Al target shows Al kα (λ=8.3A, E=1.4keV) in orders n=2 though n=7. Contamination from O kα (λ=23.6A, E=0.525keV) is also clearly present in first and second orders. Note that the blaze function is about 20 deg. in azimuthal angle. This spectrum was obtained by the XOGS spectrograph in the beam facility at Marshall Space Flight Center using a 3600 g/mm grating array in the off-plane mount. The signal in the sum of orders 3 through 6 is about 40% of the incident signal. With a CCD these orders can be recombined without loss of signal or resolution.

Off-plane Tradeoffs

PRO

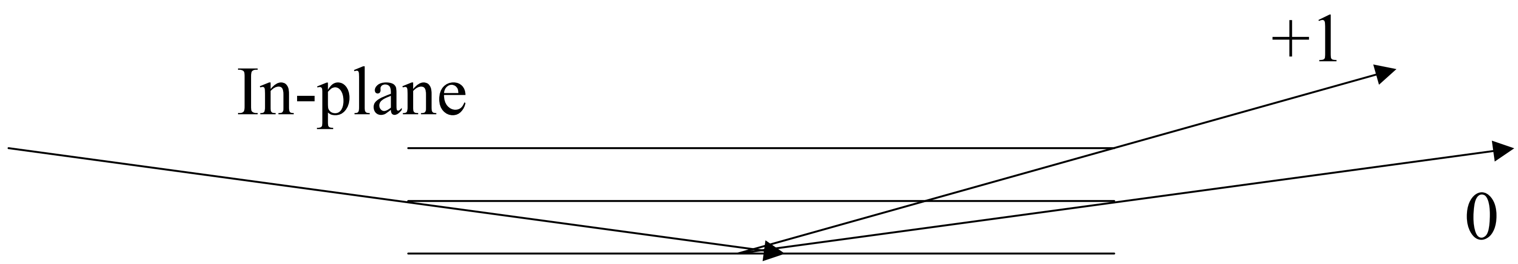
- Higher Throughput
- Higher Resolution
- Better Packing Geometry
- Looser Alignment Tolerances

CON

- Higher Groove Density

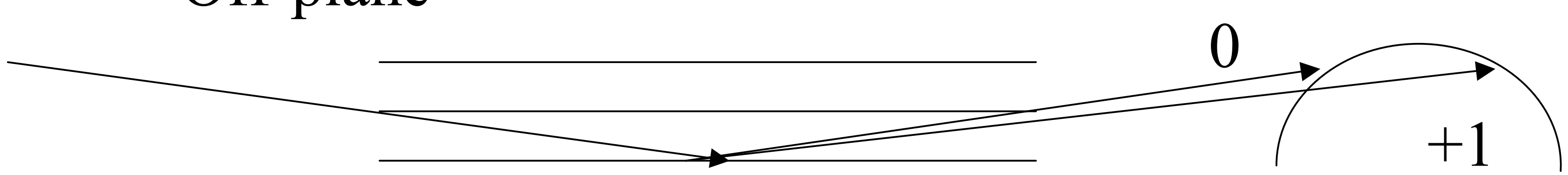
Packing Geometry

In-plane



Central grating must be removed.
Half the light goes through.

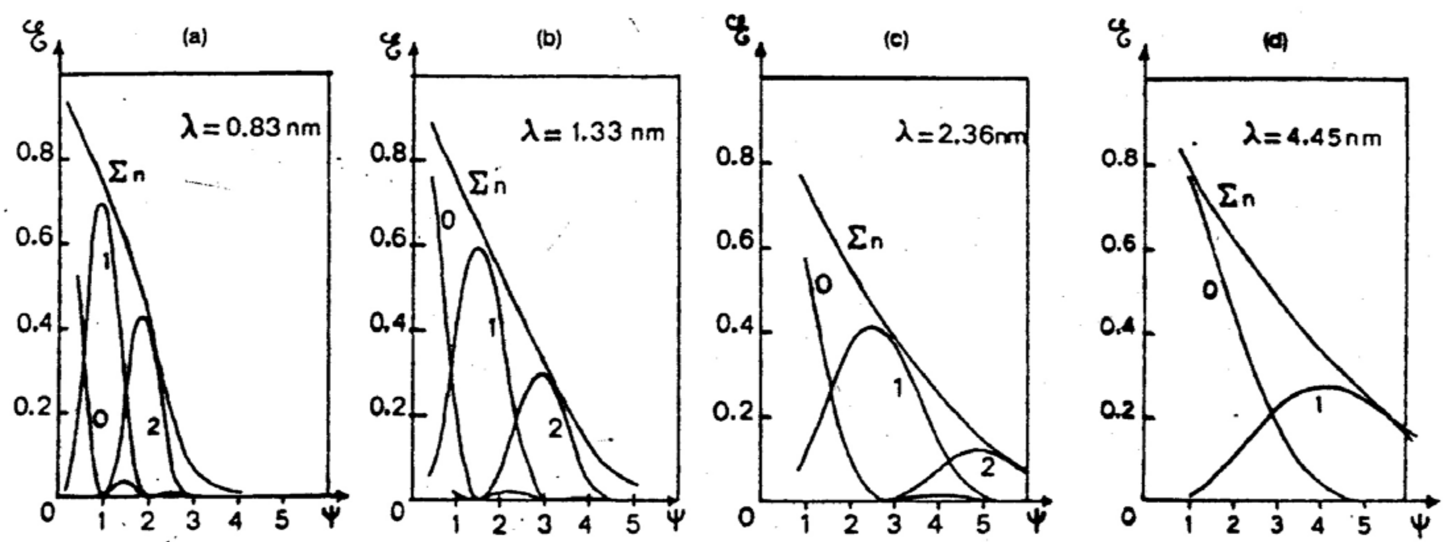
Off-plane



Gratings may be packed optimally

Throughput

- Littrow configuration α = β = blaze angle
  - Better Groove Illumination
  - Maximum efficiency
- Constant Graze Angle



Holographic Gratings

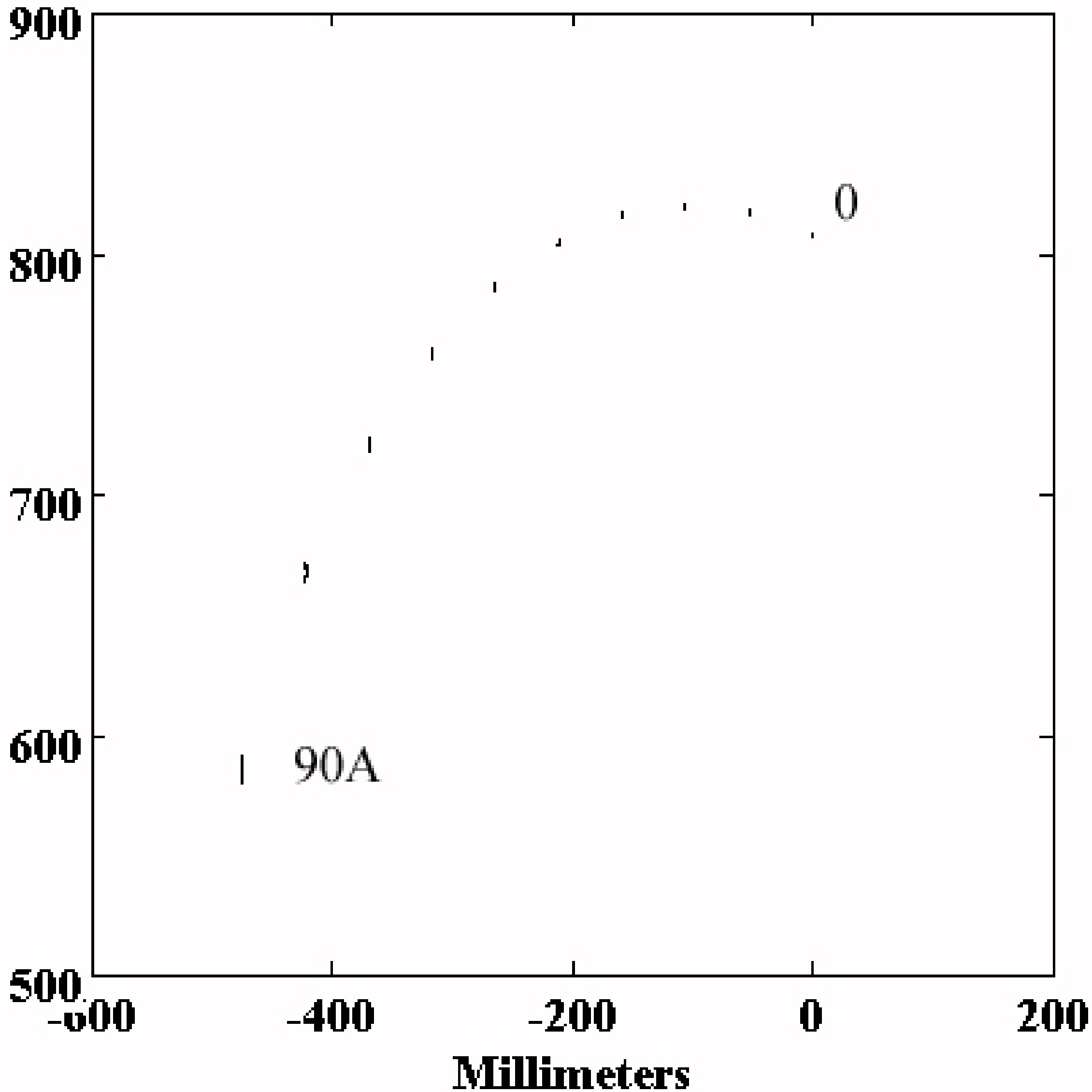
Last year we reviewed approaches to fabricating high density gratings.

At Jobin-Yvon (outside Paris)
Create rulings using interference pattern in resist
Ion-Etch Master to Create Blaze

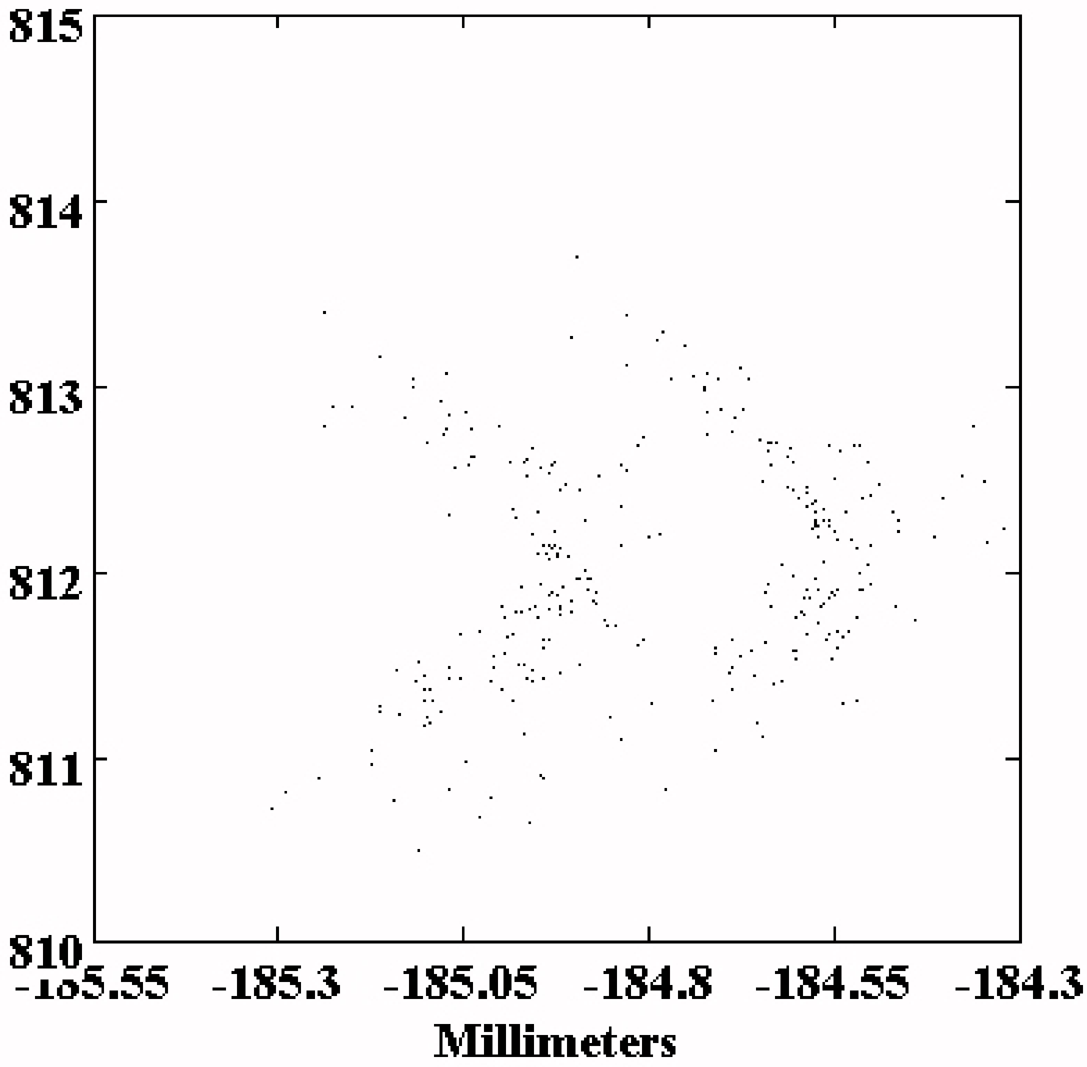
Radial Geometry – Type 4 Aberrated Beams
Density: Up to 5800 g/mm Triangular (<35 deg blaze)

In UV holographic blazed gratings have *very* low scatter and good efficiency – same in x-ray?

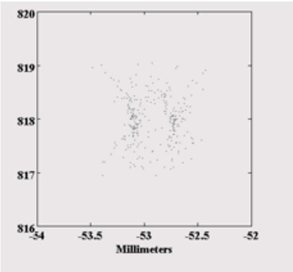
Raytracing – Arc of Diffraction



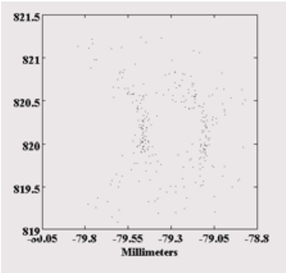
Raytrace – 35 & 35.07Å



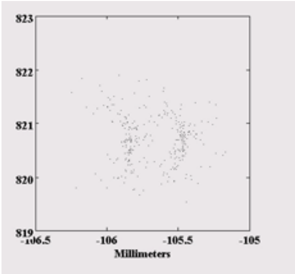
Raytracing of Wavelength Pairs
λ and λ+.07Å



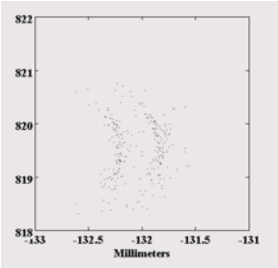
10Å



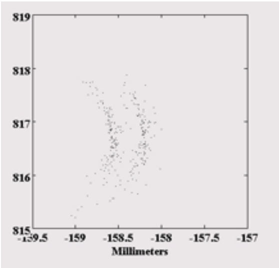
15Å



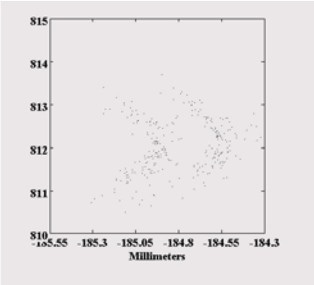
20Å



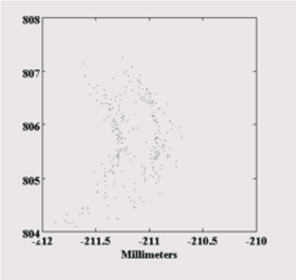
25Å



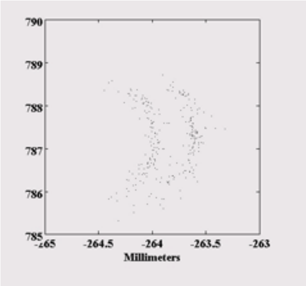
30Å



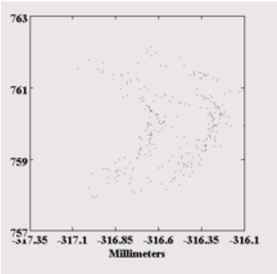
35Å



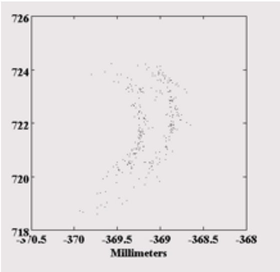
40Å



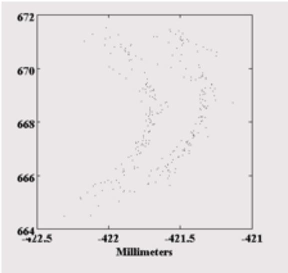
50Å



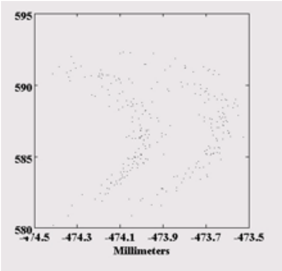
60Å



70Å



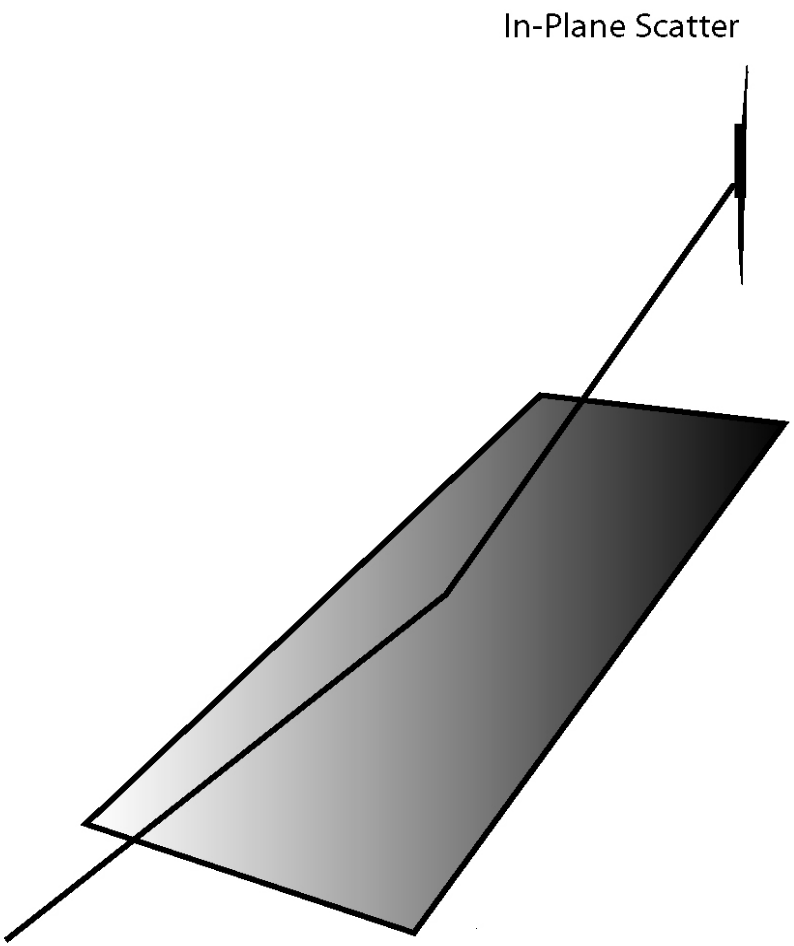
80Å



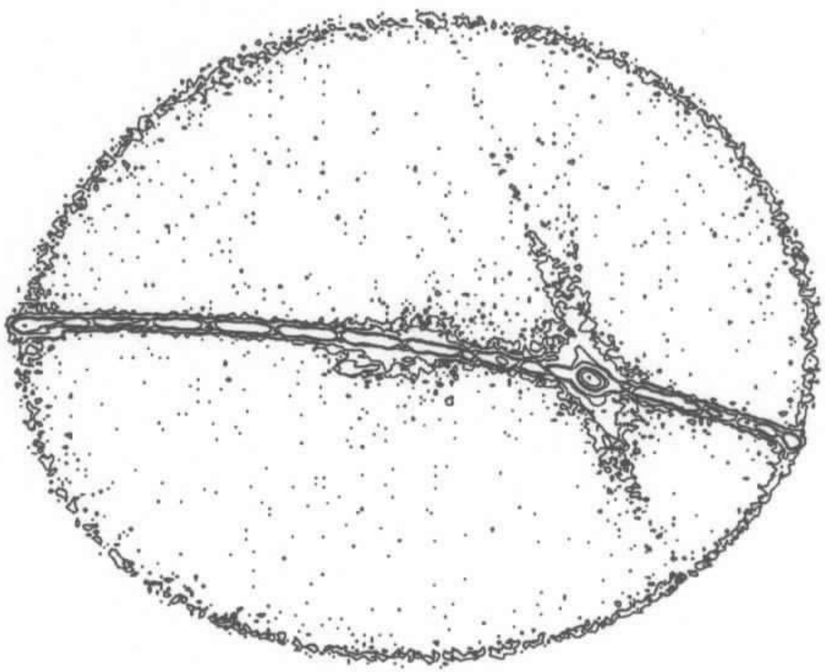
90Å

Internal Structure of Telescope

Blur Favors Dispersion in Off-plane Direction

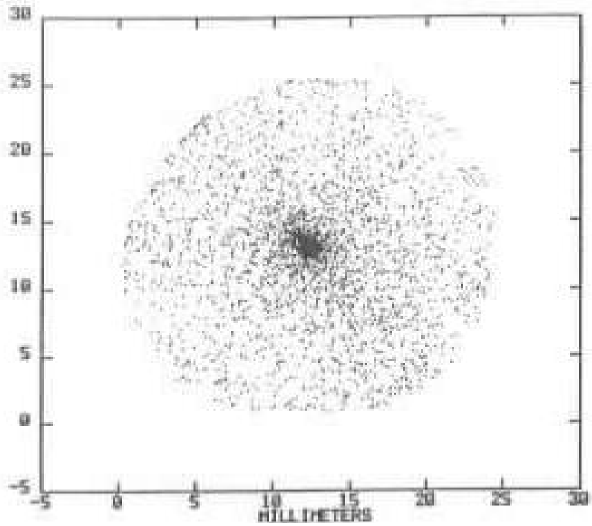


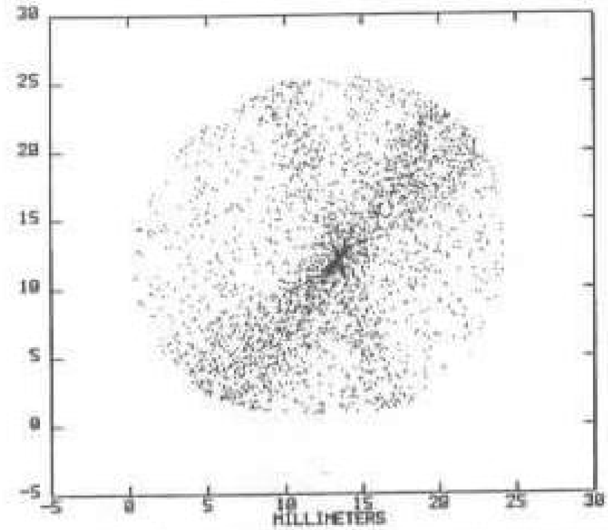
Spectral line of HeII 304Å displaying In-plane scatter

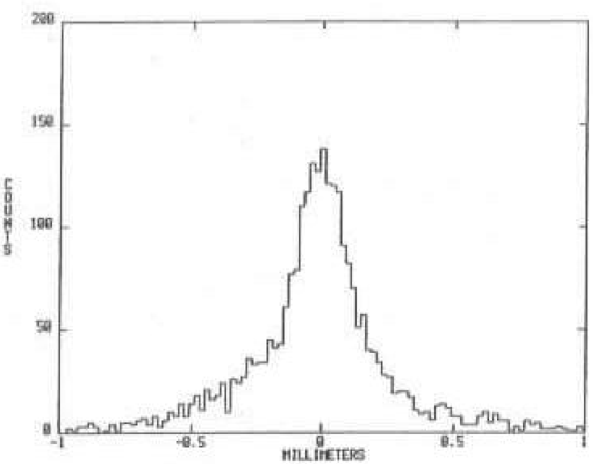


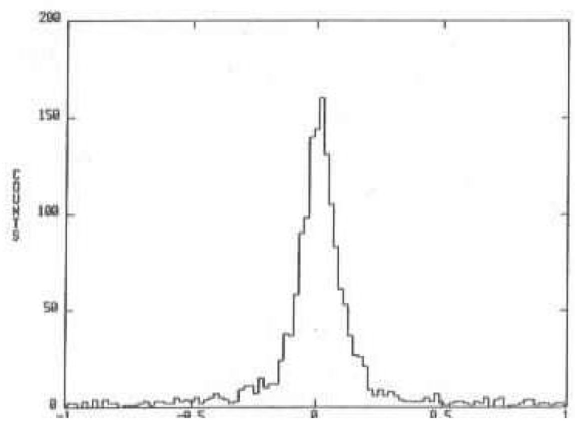
Data from a radial grating in the off-plane mount, Wilkinson

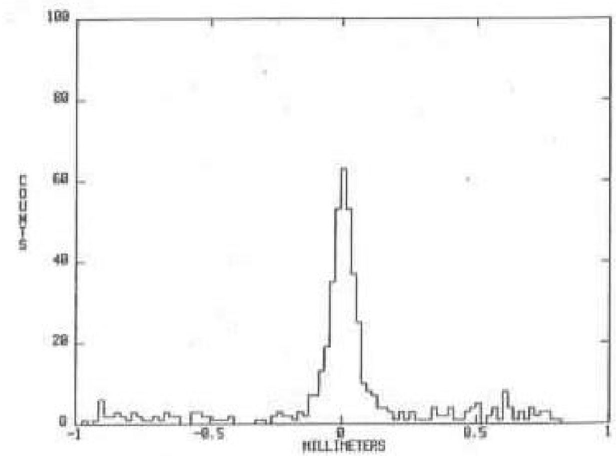
Subaperture Effect



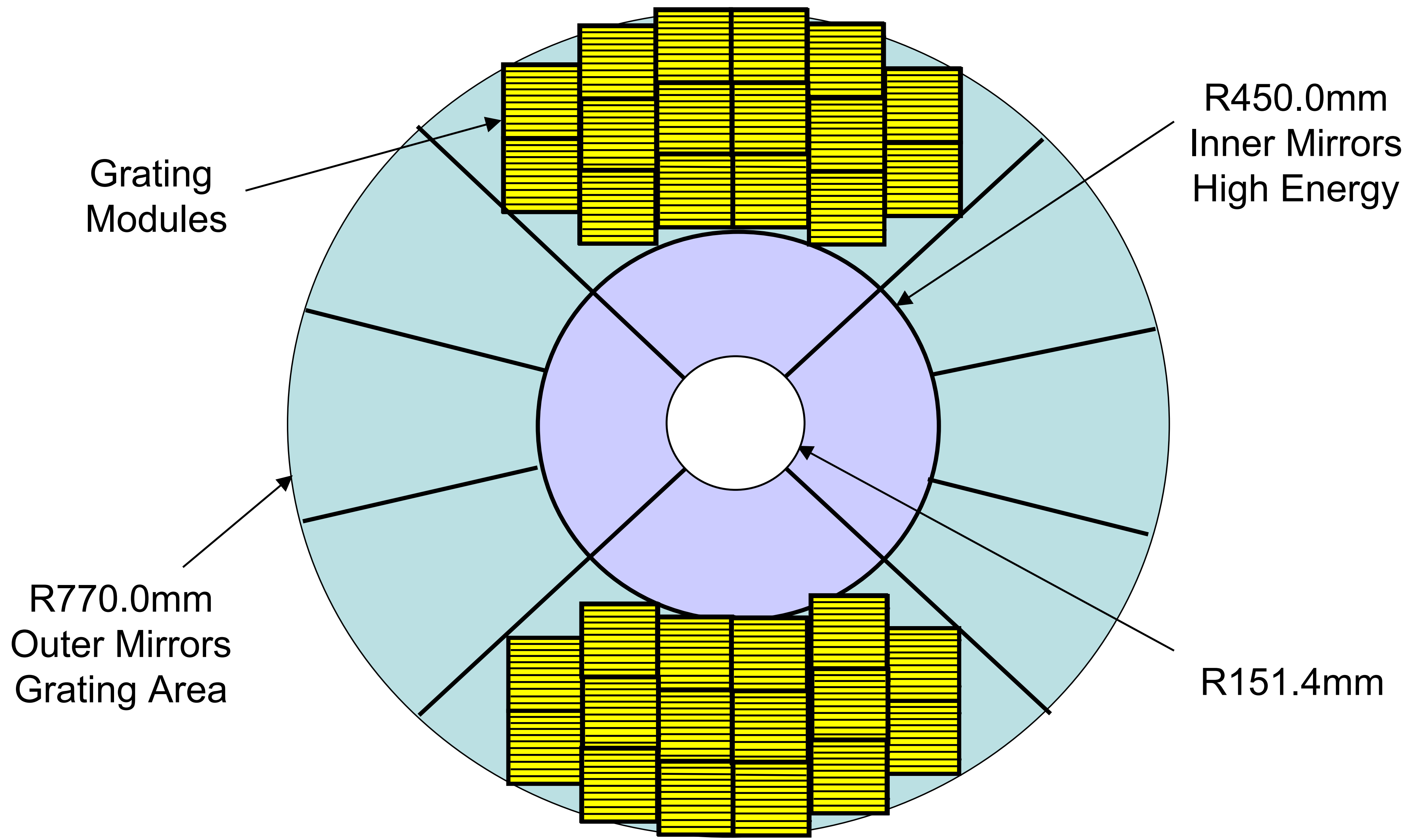




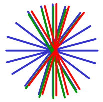




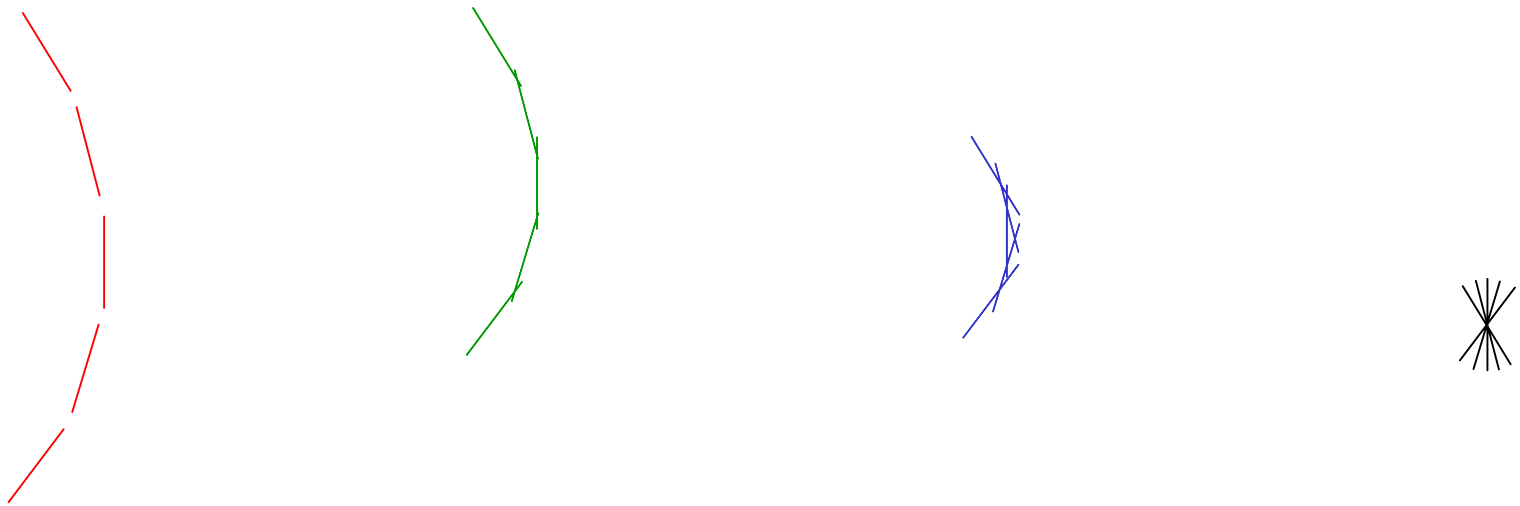
Off-plane Grating Module Locations on Envelope



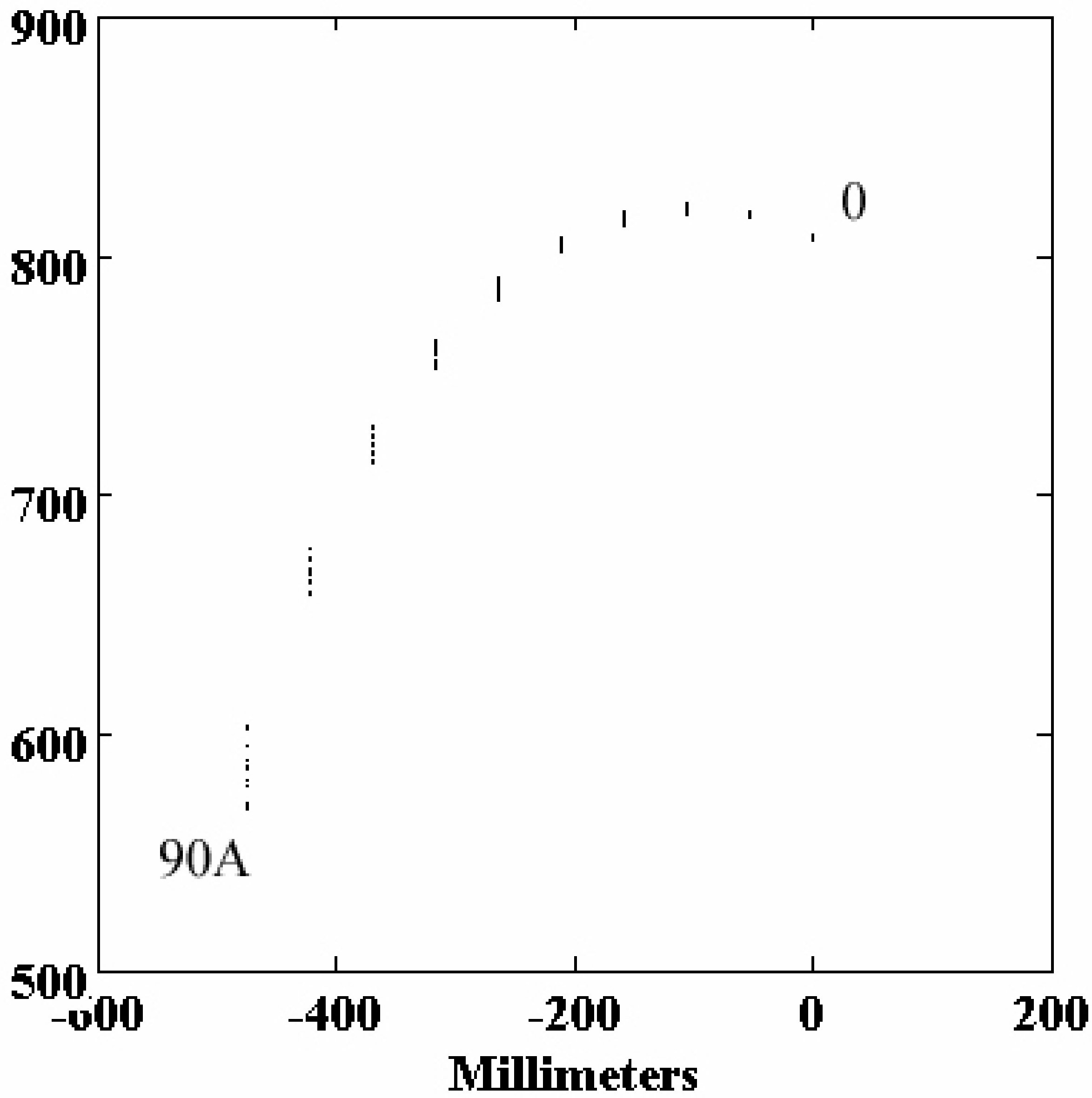
Can Improve Performance



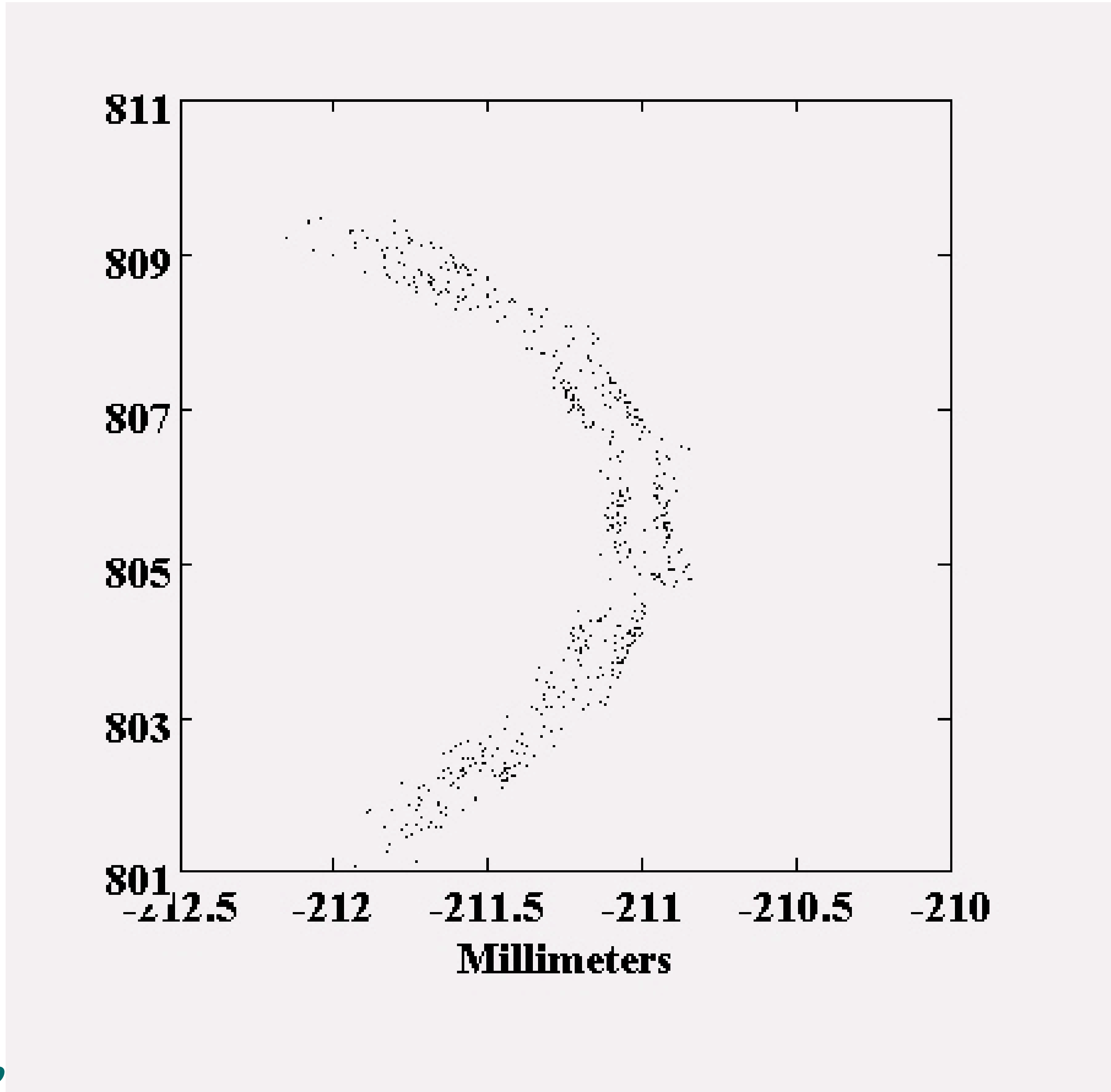
Can Improve Performance



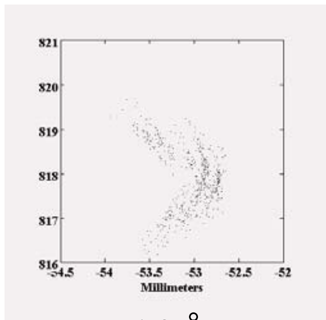
Raytracing – Arc of Diffraction



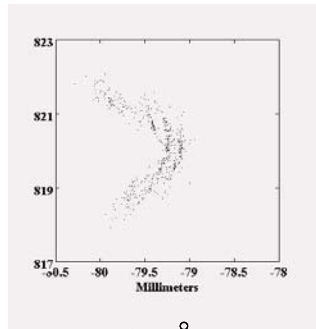
Raytrace – 35 & 35.028Å



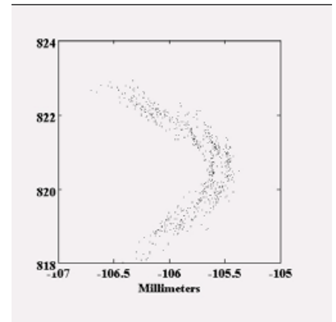
Raytracing of Wavelength Pairs
λ and λ+.028Å



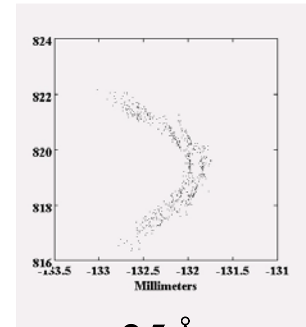
10Å



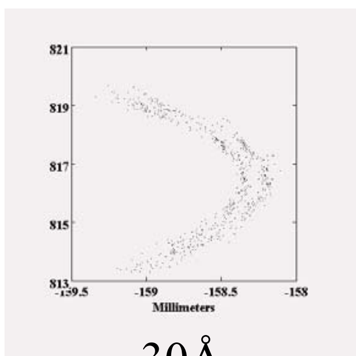
15Å



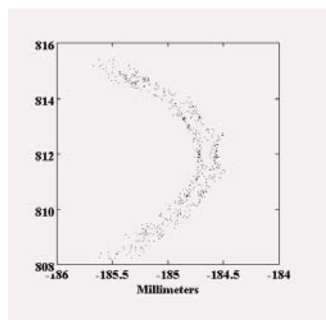
20Å



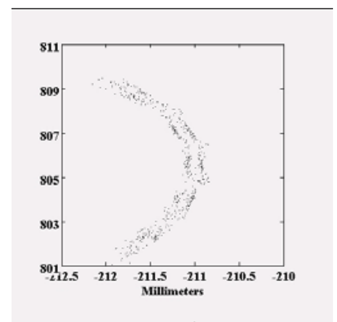
25Å



30Å



35Å



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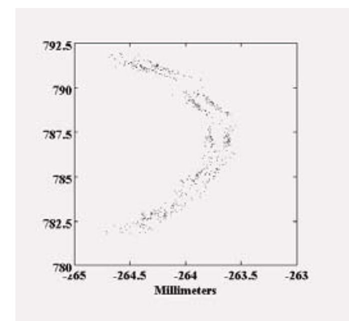
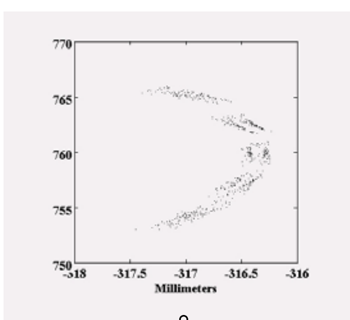


50Å



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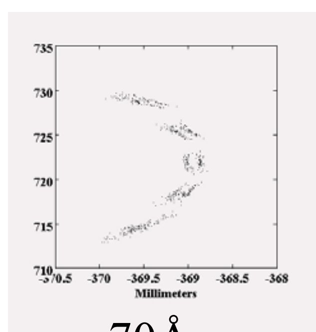
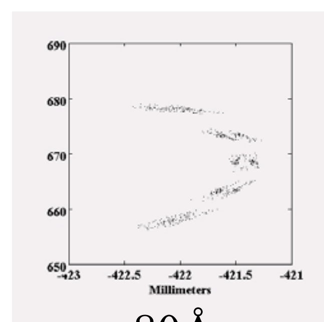


70Å



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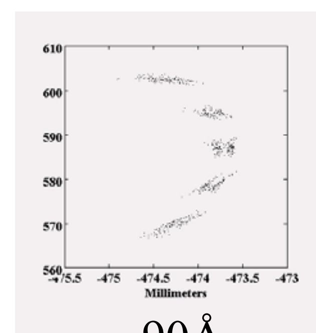

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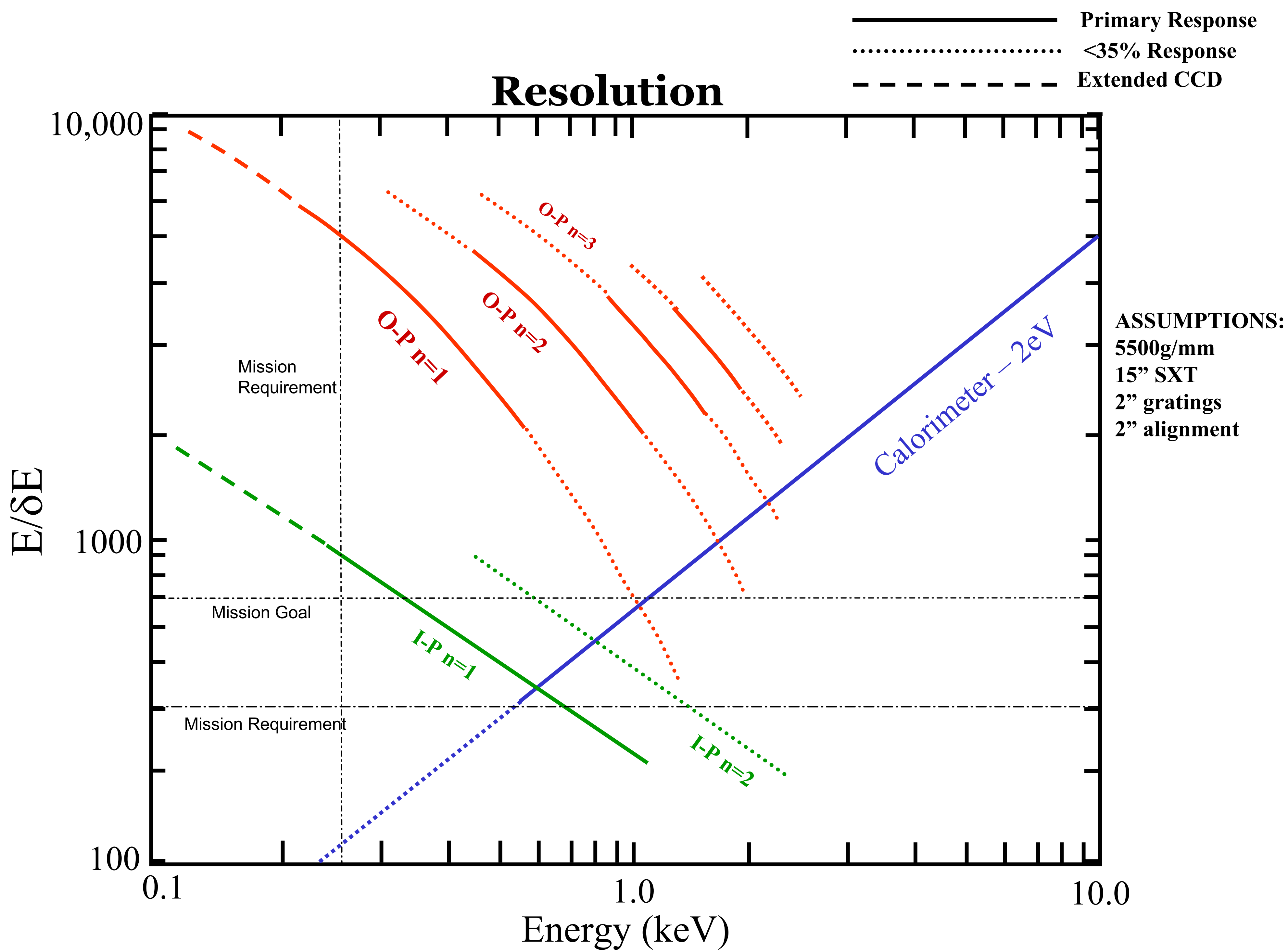
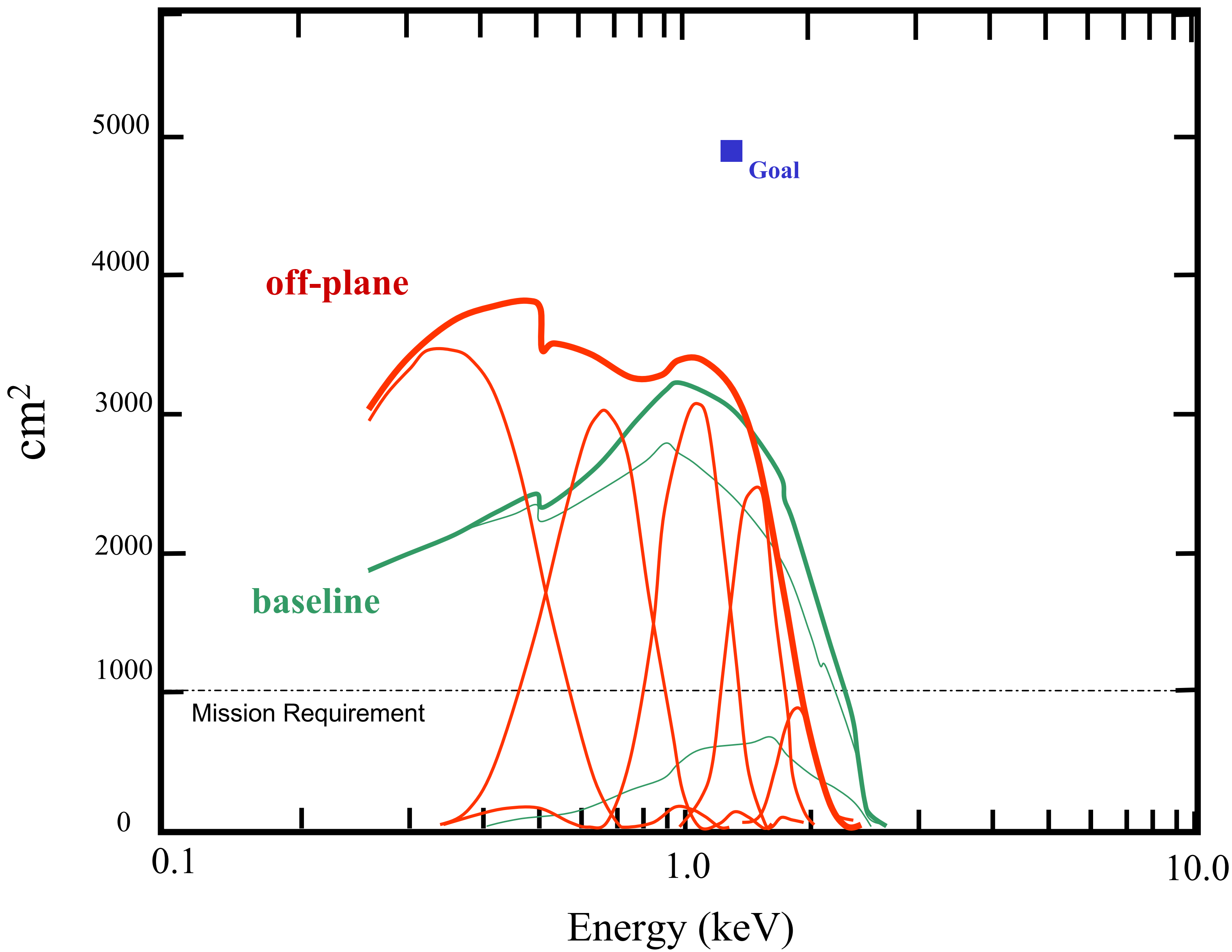


Resolution
Primary Response
<35% Response
Extended CCD
ASSUMPTIONS:
5500g/mm
15” SXT
2” gratings
2” alignment
E/δE
10,000
1000
100
0.1
1.0
10.0
Energy (keV)
O-P n=1
O-P n=2
O-P n=3
I-P n=1
I-P n=2
Calorimeter – 2eV
Mission Requirement
Mission Goal
Mission Requirement

Effective Area



ASSUMPTIONS:

Coverage 40% of outer envelope

Off-Plane Groove Efficiency 80% of theoretical

85% Structure Transmission

CCD thin Al filter only

Figure of Merit

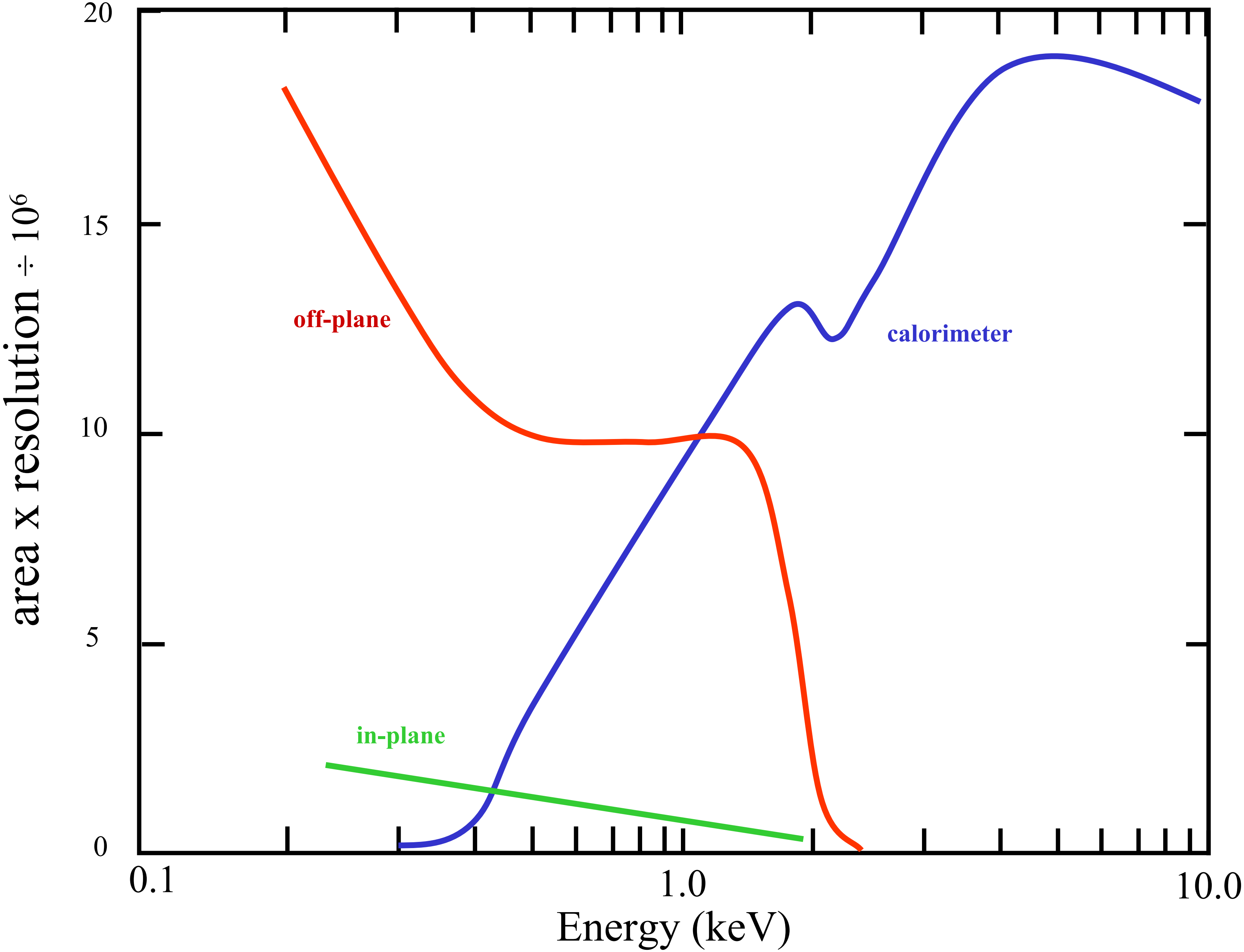
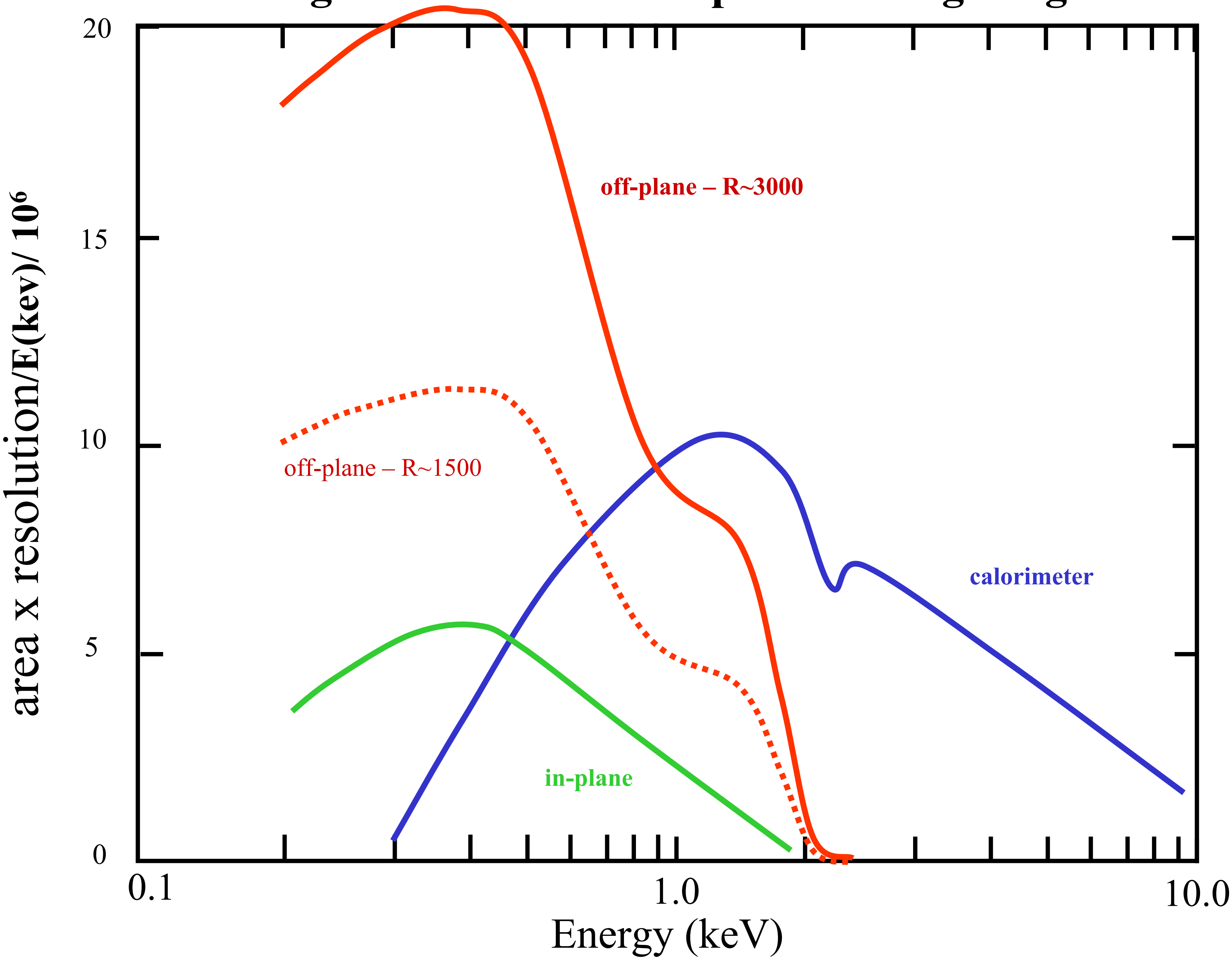


Figure of Merit with Spectral Weighting



Pros & Cons of Off-plane vs. Baseline Design

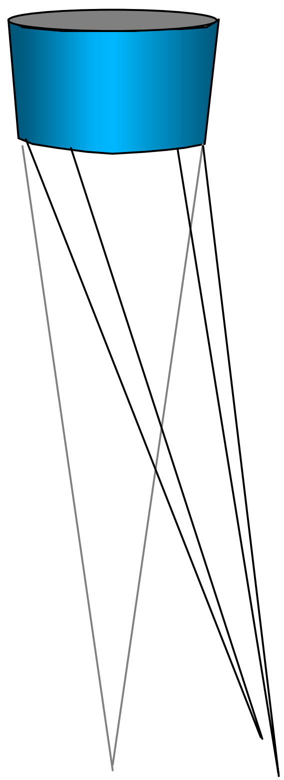
- Pro:
  - Greater Resolution from Sub-aperturing
  - Greater Collecting Area – higher groove efficiency
  - Less Sensitivity to Grating Alignment
  - Less Sensitivity to Grating Flatness
  - Lower scatter in Dispersion Direction
  - Fewer Gratings Required
  - Thicker Substrates Acceptable
  - Smaller Structure Required

- Con:
  - Higher groove density required

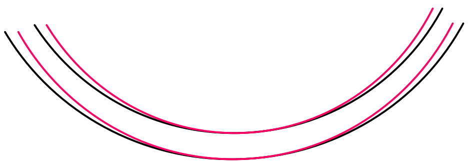
Difficulties of High Resolution ($\lambda/\Delta\lambda > 1200$)

- flatter gratings
- tighter alignment
- tighter focus
- telescope depth of focus adjustment
- zero order monitor essential to aspect solution
- more difficult calibration
- greater astigmatism
  – higher background
  – more source overlap

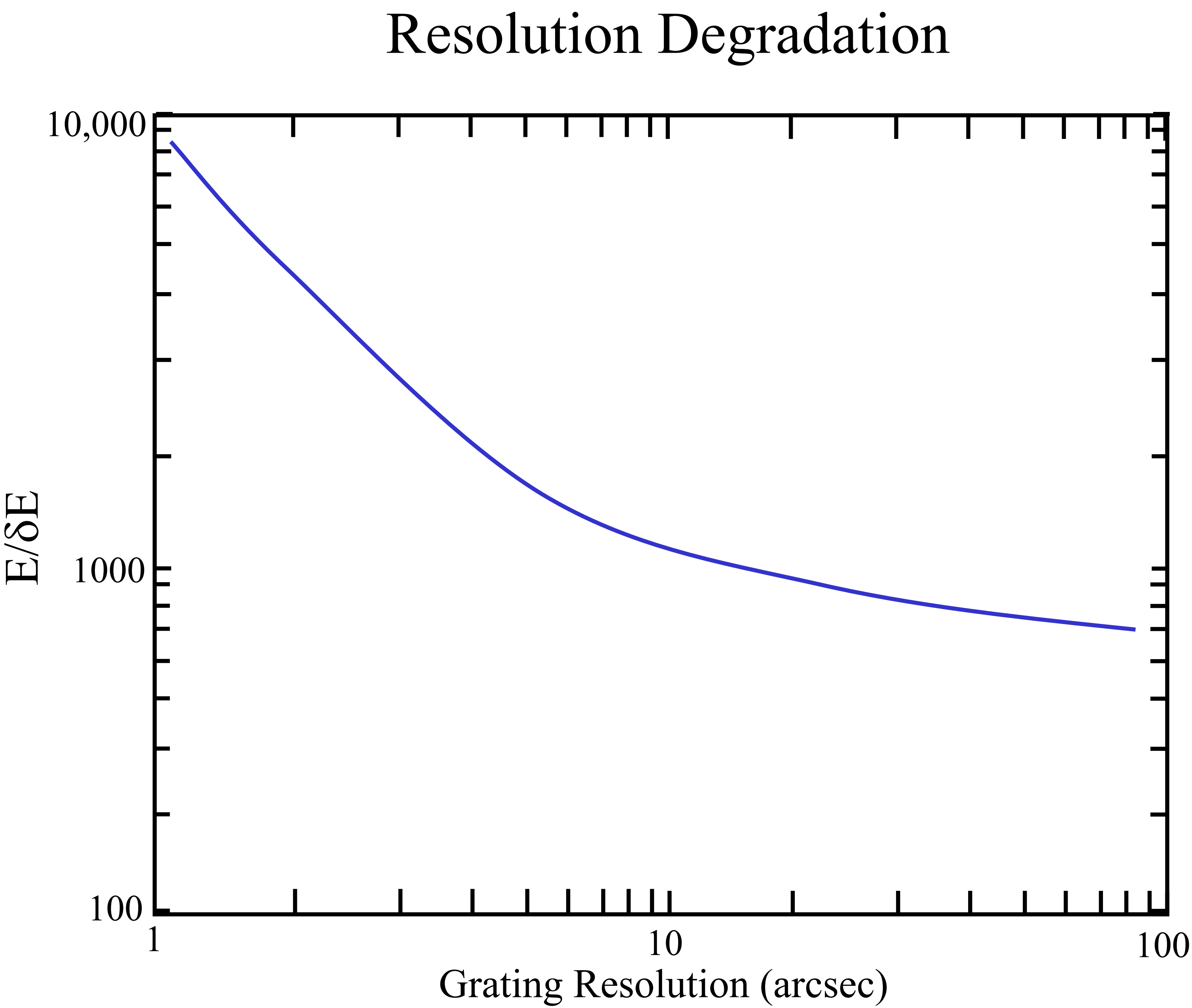
Depth of Field Problem



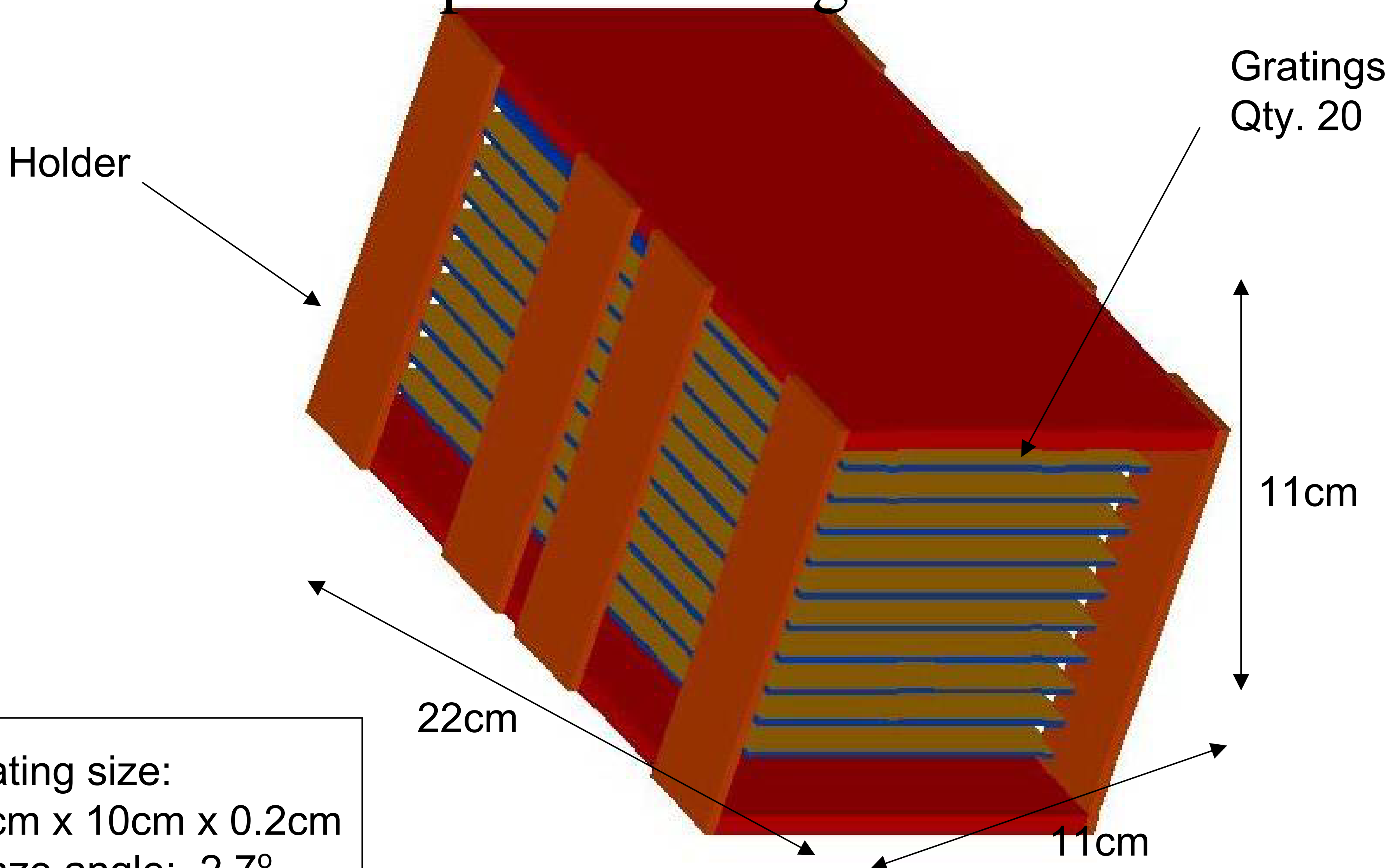
Solutions for Study:
Smaller Gratings
Curved Gratings
Adjust Telescope Segments



Hope that it is merely a matter of mounting existing shells at different radii


Resolution Degradation
10,000
1000
100
E/δE
1
10
100
Grating Resolution (arcsec)

Off-plane Grating Module



Grating size:
10cm x 10cm x 0.2cm
Graze angle: 2.7º

Off-plane Grating Resolution Options

$\lambda/\delta\lambda \sim 1000$	$\lambda/\delta\lambda \sim 5000$
• SXA (Al/SiC) substrates	• Glass/Si substrates?
• Easy tolerances	• More difficult tolerances
• Simple mount	• More difficult mount
• No thermal gradient	• Probable thermal gradient issues
• Mass OK	• Mass constraint more difficult to meet

Off-plane Grating Estimated Tolerances

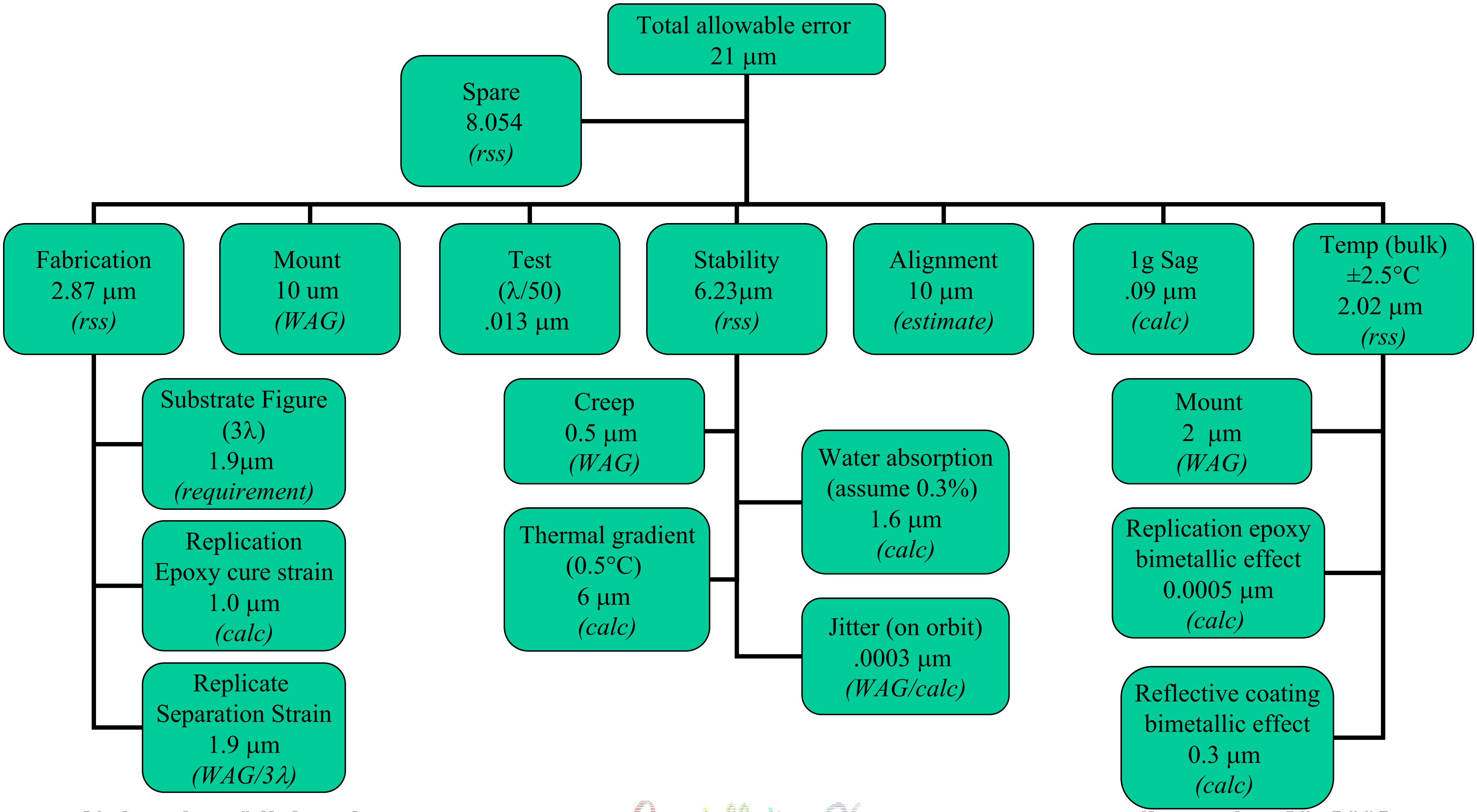
Error type	Zero-order Allowable Tolerances		
	Equation	ω = 15 arcsec	ω = 2 arcsec
Surface error	$\delta = \frac{s}{20}$	36.5μm	4.9μm
δ_x	$\delta_x = \frac{s}{20 \cos \theta}$	36.5μm	4.9μm
δ_y	$\delta_y = \frac{w}{10}$	1mm	1mm
δ_z	$\delta_z = \frac{s}{20\, sin\, \theta}$	775μm	103μm
θ_x	$\sin \phi = \frac{w}{5h}$	11.5°	11.5°
θ_y	$\phi = \frac{\omega}{20}$	0.75 arcsec	0.1 arcsec
θ_z	$\phi = \frac{\omega}{10 \sin \theta}$	31.8 arcsec	4.2 arcsec

Off-plane Grating Module Estimated Mass

Materials	Gratings (Kg)	Holder (Kg)	Light-weight	One Module (Kg)	Qty Modules	Total mass (Kg)
SXA/SXA	1.16	1.20	none	2.36	32	75.65
SXA/SXA	1.16	1.20	25%	2.17	32	69.53
SXA/6061	1.16	1.11	none	2.27	32	72.73
FS/Invar/Ti	0.88	1.568	70%	2.45	32	78.36
FS/Titanium	0.88	1.488	30%	2.37	32	75.82
FS/GrEp/Invar	0.88	1.687	none	2.57	32	82.17

Wavefront Error: Resolution 1000

Constellation X Off-plane Grating Mount rms Wavefront Error Budget (15 arcsec max)
All errors are presented as rms wavefront error



Wavefront Error: Resolution 5000

Constellation X Off-plane Grating Mount rms Wavefront Error Budget (2 arcsec max)
All errors are presented as rms wavefront error

- Total allowable error 2.77 mm
  - Spare 0.754 µm *(rss)*
  - Fabrication 1.16 µm *(rss)*
    - Substrate Figure (1.5λ) 0.95 µm *(requirement)*
    - Replication Epoxy cure strain 0.23 µm *(calc)*
    - Replicate Separation Strain 0.6 µm *(WAG/1λ)*
  - Mount 1.5 µm *(WAG)*
  - Test (λ/50) .013 mm
  - Stability 0.62 µm *(rss)*
    - Creep 0.1 µm *(WAG)*
    - Thermal gradient (0.1°C) 0.5 µm *(WAG/calc)*
    - Water absorption (assume 0.3%) 0.35 µm *(calc)*
    - Jitter (on orbit) .0003 µm *(WAG/calc)*
  - Alignment 1.75 µm *(estimate)*
  - 1g Sag .11 µm *(calc)*
  - Temp (bulk) ±2.5°C 0.21 µm *(rss)*
    - Mount 0.2 µm *(WAG)*
    - Replication epoxy bimetallic effect 0.008 µm *(calc)*
    - Reflective coating bimetallic effect .07 µm *(calc)*

Off-plane Grating Prototype: steps and schedule

Phase	Task	Leadtime
1	Preliminary feasiblility study of type 4 aberration corrected grating distribution to approximate radial distribution	4-5 mos. (Jun ‘02 to ~Oct ‘02)
2	Preliminary study of blaze process using existing masks (30^o profile goal). (work done in parallel with step 1)	4-5 mos. (Jun ‘02 to ~Oct ‘02)
3	Contingent upon step 1&2 positive result. Deliverable: 58x58x10mm parallel groove sample with 30^o blaze angle.	4 mos. (Oct ‘02 to ~Feb ‘03)
4	Contingent upon positive test of sample. Deliverable: 58x58x10mm radial groove distribution with blazed profile.	3 mos. (Mar ‘03 to ~Jun ‘03)
5	Ray-tracing to optimize recording configuration Deliverable: 120mm square radial distribuation with blazed profile and flight groove density.	TBD

In Conclusion, Off-plane Can:

- Match RGS to Calorimeter Scientifically
  - R~1500
  - greatly eased tolerances
- or Significantly Enhance Con-X Science
  - R~3000
  - tolerances at currently expected levels

Study funded by the Con-X project. First results in January.